PB87-104634

Convective Diffusion Field Measurements Compared with Laboratory and Numerical Experiments

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

Oct 86

U.S. Department of Commerce
National Technical Information Service
NTIS

PB87-104634

EPA/600/D-86/236
October 1986

CONVECTIVE DIFFUSION FIELD MEASUREMENTS COMPARED WITH LABORATORY AND NUMERICAL EXPERIMENTS

by

G. A. Briggs
Atmospheric Sciences Research Laboratory
Research Triangle Park, NC 27711

W. L. Eberhard, J. E. Gaynor, W. R. Moninger, and T. Uttal
Wave Propagation Laboratory
National Oceanic and Atmospheric Administation
Boulder, CO 80303

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/D-86/236	2.
3. RECIPIENT'S ACCESSION NO. PB87 104634/AS	
4. TITLE AND SUBTITLE Convective Diffusion Field Measurements Compared with Laboratory and Numerical Experiments	5. REPORT DATE October 1986 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) G. A. Briggs*, W. L. Eberhard, J. E. Gaynor, W. R. Moninger, T. Uttal	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS *Meteorology Div., ASRL, RTP, NC 27711 Wave Propagation Lab. NOAA/ERL Boulder, CO 80303	10. PROGRAM ELEMENT NO. CDTA1D/03-6086 (FY-86) 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory--RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

Some of the more fundamental diffusion parameters measured in the CONDORS convective diffusion field experiment are compared with laboratory experiment and numerical modeling results by means of nondimensionalizations using convective scaling (i.e., mixing depth, z_i, for length and w* for velocity). The CONDORS experiment used remote sensors, radar and lidar, to measure three-dimensional patterns of metalicized "chaff" and oil fog. The growth of the vertical standard deviation of plume distribution, σ_z, agrees quite well with the non-field results, approximating 0.6 w*t nearly to the point of limitation by capping at $z = z_i$. The lateral standard deviation, σ_y, also tends to approximate 0.6 w*t for most elevated releases, while most surface releases show slower growth at large t that better approximates the non-field results. Surface patterns of crosswind-integrated concentration show remarkable agreement with the laboratory results, for the most part, although there is more variation in individual runs; peak values from elevated releases are of the order of 70% larger than conventional Gaussian model predictions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 7
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

CONVECTIVE DIFFUSION FIELD MEASUREMENTS COMPARED WITH LABORATORY AND NUMERICAL EXPERIMENTS

G. A. Briggs*

Atmospheric Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

W. L. Eberhard, J. E. Gaynor, W. R. Moninger, and T. Uttal

Wave Propagation Laboratory
National Oceanic and Atmospheric Administration
Boulder, CO 80303

1. INTRODUCTION

Both the convective tank diffusion experiments of Willis and Deardorff (WD) (1976, 1978, 1981) and the large eddy numerical simulations of particle diffusion of Lamb (1978, 1979) gave results that differed fundamentally from conventional, Gaussian models, although they agreed well with each other. In both sets of experiments, the vertical mode of time averaged concentrations (X) descended almost to the surface from elevated sources, but lifted off the surface from near-surface releases after a certain time following release (about 0.5 z_i/w^*, where z_i is the mixing depth and w^* is the convective scale velocity). Explanations of these behaviors have been made in terms of the structure of fields of large convective eddies, but full-scale experiments with three dimensional plume measurements were needed to make the results fully convincing. This was the purpose of the CONDORS experiments, carried out in 1982 and 1983 at the Boulder Atmospheric Observatory (BAO) by NOAA's Wave Propagation Laboratory and Air Resources Laboratory Field Laboratory, under interagency agreements with EPA. This paper briefly describes the measurements and presents some limited comparisons of the field results with the laboratory and numerical results.

2. THE MEASUREMENTS

CONDORS was the first basic diffusion experiment to fully map plumes on scales of several kilometers in all three dimensions. This was done with two independent tracers, so that simultaneous surface and elevated releases were possible. Oil fog was mapped by lidar through vertical scans at about six azimuths ranging from 0.2 to 2.9 km from the source. "Chaff", a metalicized mylar thread, was mapped by Doppler radar and processed into Cartesian coordinates. Lidar and radar scans were repeated every 2 or 3 minutes so that ensemble averages could be obtained. In addition, in 1983 a single arc of surface samplers was operated with SF6 and 1381 tracers released next to the chaff and oil fog release points. This was done to check the assumption that conservative tracer X/Q values could be approximated by replacing Q, the release rate, with local fluxes of oil fog, which suffers some vaporization loss, and chaff, which suffers some deposition loss. The experimental layout, tracer characteristics, lidar and radar data acquisition and processing, and meteorological measurements are briefly described in earlier conference papers by Moninger et al. (1983) and Eberhard et al. (1985); they are fully described in the recently released CONDORS data report (Kaimal et al., 1986). Space is lacking to repeat these descriptions here.

Two hour releases were made near midday on 12 sunny days in late summer, while rawinsonde releases and eight levels of sophisticated instrumentation on the 300-m BAO tower provided excellent meteorological measurements; 17 periods of relatively steady conditions lasting from 29 to 60 minutes were selected for processing and averaging.

3. METHOD OF ANALYSIS

Comparison of field, laboratory, and numerical model results is relatively straightforward if all quantities are nondimensionalized in terms of the convective turbulence scales suggested by Deardorff (1970). This scaling has proven very useful for describing both turbulence and diffusion in convective boundary layers (Briggs, 1985). (Convective conditions dominate over land surface during daylight except when there is a high wind, an overcast sky, or snow cover.) Plume dimensions are divided by z_i, which is both the effective limit to vertical diffusion and the length scale characterizing horizontal dimensions of updrafts (thermals) and downdrafts. Great care was used in estimating z_i for CONDORS periods, by looking for consensus among nine different indicators (Kaimal et al., 1986). The scale that best characterizes convective turbulence velocities is $w^* = (H^* z_i)^{1/3}$. (Neglecting a small contribution to buoyant acceleration flux by water vapor flux, $H^* = (g/T)\overline{w'T'}$, where g is gravitational acceleration, T is absolute temperature, and w is vertical velocity; the covariance $\overline{w'T'}$ was measured directly at the lowest tower levels.) Thus, the time scale characterizing convective diffusion is z_i/w^*; assuming a transport time $t = x/\bar{u}$, where x is distance downwind of the source and $\bar{u}$ is the mean wind speed measured at the upper tower levels; all variables are plotted here against the nondimensionalized distance $X = (x/\bar{u})w^*/z_i$.

* On assignment from the National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce

While actual period durations, τ, ranged from 29 to 60 min, an important consideration for ensemble averaging is the number of individual thermals or downdrafts that could pass by a fixed point during these periods. The appropriate "eddy passage" time scale is about $1.5\ z_i/\bar{u}$. The ratio $\tau\bar{u}/z_i$ ranged from 2.8 to 19.4, a factor of seven. This is quite significant, so we have indicated three groups of $\tau\bar{u}/z_i$ by symbol sizes (see table, below).

Another important variable is the ratio of source height to z_i, designated here as Z_s. The CONDORS data fall into four groups of similar Z_s. The largest values, 0.43 ± 0.02, are associated with two periods in the largest $\tau\bar{u}/z_i$ group. For economy of space, these periods are plotted here with the $Z_s = 0.17$ to 0.25 group, which are distinguishable by smaller symbol sizes (smaller $\tau\bar{u}/z_i$ ranges) The $Z_s = 0.32$ to 0.34 range provides the largest amount of elevated source data, all with collocated releases of chaff and oil fog so that direct comparisons can be made (the same is true of the $Z_s = 0.43$ group). The surface releases were predominately oil fog and the $Z_s = 0.2$ cases were predominately chaff.

4. SOME RESULTS AND COMPARISONS

Figure 1 shows the standard deviations of lateral plume material position, σ_y, divided by z_i and versus X. The $Z_s = 0.32$ an 0.43 groups show good consistency between oil fog and chaff measurements. Chaff σ_y tends to be somewhat larger than oil fog σ_y at small x; this may be due to the relatively crude lateral resolution of the radar (about 160 m). Clearly, many of the σ_y/z_i values in the smallest $\tau\bar{u}/z_i$ range fall short of the others. This also occurs, to a somewhat lesser extent in the σ_z/z_i plots of Figure 2. We conclude that $\tau\bar{u}/z_i > 5$ is required for adequate ensemble averaging in convective conditions. When such is the case, most $Z_s = 0$ and 0.2 cases approximate the expression $\sigma_y/z_i = 0.6X/(1 + 2X)^{1/2}$ suggested by Briggs (1985). This is also a reasonably good approximation to the WD tank results for all release heights and to Lamb's calculation for a near-surface release (his elevated-source σ_y/z_i values were about 30% less at $X < 0.5$). However, most $Z_s = 0.32$ and 0.43 cases better approximate simple linear growth, $\sigma_y/z_i = 0.6X$ (i.e., $\sigma_y = 0.6\ w^*t$) We believe that, in many cases, σ_y growth at larger X is enhanced at the BAO site due to a large directional wind shear between the westerly flow aloft and the easterly flow within the mixing layer (this flow is often driven by upslope flow on the heated eastern slopes of the Rocky Mountain Front Range, beginning 25 km west of the BAO). Future analyses will consider whether there is a correlation between σ_y/z_i and wind shear.

TABLE OF SYMBOLS

TRACER/ DECTECTOR	DURATION $\tau\bar{u}/z_i$ RANGES		
	2.8 - 4.3	5.2 - 7.9	12.2 - 19.4
OIL FOG/LIDAR	○	○	○
CHAFF/RADAR	△	△	△
GAS/SAMPLERS	■	■	■

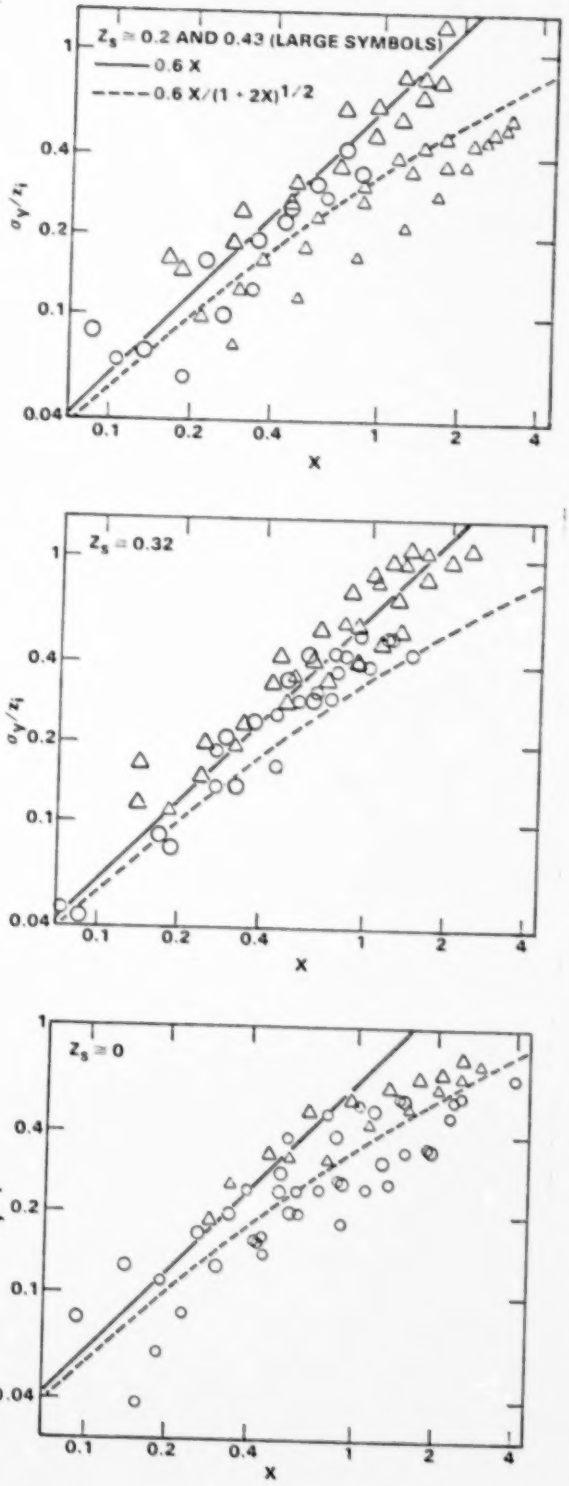

Fig. 1 Vertically averaged σ_y/z_i vs. X for four groupings of Z_s compared with simple analytical fits.

Figure 2 shows the standard deviations of plume material height, σ_z, divided by z_i and versus X. Except for the small $\bar{u}/z_i$ case, the elevated-source cases show remarkable consistency for field experiment data. At small X the data approximate the same asymptote as for σ_y, $\sigma_z = 0.6\ w^*t$; this is consistent with statistical diffusion theory and turbulence velocity variances $= 0.6w^*$. The surface-source data, excluding many small $\bar{u}/z_i$ cases, approximate this also, but with somewhat more scatter. At $X < 0.6$, chaff σ_z has a tendency to be smaller than oil fog σ_z. Much of this is due to blockage of most radar signal in the lowest 60 m by terrain and the necessary removal of signal contaminated by ground clutter (strong reflections from surface objects). Because of this and the uncertain effect of the chaff's settling speed, about 0.3 m/s, chaff was not used as a surface source in 1983. The lidar usually scanned to within 20 m of the surface, but some clearance was required because the laser beam was not eye-safe. At larger X, data for all Z_s converge in the neighborhood of $\sigma_z/z_i = 0.27$. This is slightly short of the asymptote for uniform mixing between $z = 0$ and z_i, $(12)^{-1/2} = 0.289$. Again, this is partly due to missing detection of plume material near the ground. In spite of gravitational settling, the chaff that remains suspended (does not deposit) appears to fully mix upward to z_i just as well as the oil fog does. This observation is further supported by plots of mean material height, $\bar{z}$, omitted here due to restricted space. All of the CONDORS data were well approximated by the simple expression $\sigma_z = 0.6\ w^*(x/\bar{u})/(1 + 5X^2)^{1/2}$. This also is a good approximation to the WD results at $X < 1.5$ for $Z_s = 0.24$, but is less so for their surface source σ_z values.

The most controversial aspects of WD's and Lamb's results are the large departures of vertical diffusion behaviors from predictions of conventional, Gaussian models, especially the increased maximum surface χ from elevated sources due to downward motion of the mode of χ. The CONDORS near-surface values of $\int \chi dy$ for the $Z_s = 0.32$ cases, plotted here in Fig. 3, clearly support these results, except for one rather erratic period (9-83). The plotted nondimensional quantity is $C_y = \bar{u} z_i \int \chi dy / Q$. For uniform mixing of a conserved tracer between $z = 0$ and z_i, $C_y = 1$. If anything, high C_y near the surface tends to persist to a somewhat larger X than given by WD.

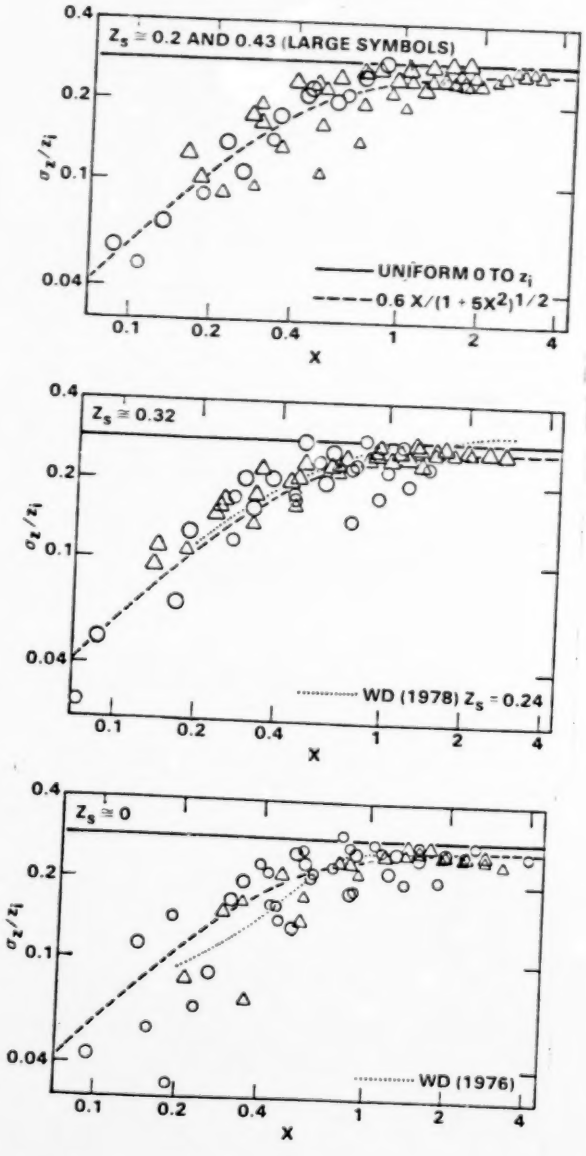

Fig. 2. Vertically averaged σ_z/z_i vs. X for four groupings of Z_s compared with WD (1976, 1978) and a simple analytical fit.

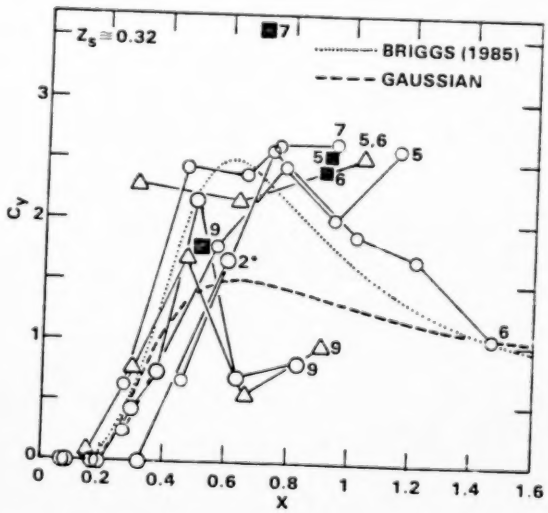

Fig. 3. Near-surface dimensionless crosswind integrated concentrations, C_y, vs. X for $Z_s = 0.32$ compared with the Briggs (1985) analytical approximation to WD's laboratory results and the Gaussian plume equation (using $\sigma_z = 0.5w^*t$). Numbers indicate period number (1982 if asterisked, otherwise 1983).

The WD results are represented in Fig. 3 by the Briggs (1985) interpolation equation, a somewhat lengthy analytical expression designed to fit their three tank experiments, which were carried out only for Z_s = 0.067, 0.24, and 0.49. The Gaussian model prediction is plotted by assuming $\sigma_z = 0.5w^*t$, somewhat smaller than the measured small-X asymptote; a different choice for σ_z growth would shift the peak in X, but would not change the magnitude of C_y. The oil fog data shown in Figs. 3 and 4 are straightforward, being from the lowest layer with complete, or nearly complete, lidar coverage (compensation factors were applied in the "nearly complete" cases). However, the chaff data were manipulated to compensate for blockage and for gravitational settling (contact the first author for details). If the blockage exceeded a factor of 2, as it did for period 7-83 and all 1982 periods, the data were not used.

Figure 4 shows near-surface C_y versus X for all surface-released oil fog measurements. Except for period 4-82, these measurements at $X < 0.5$ are consistent with Nieuwstadt's (1980) theoretical/empirical fit to the Prairie Grass field experiment measurements of 1956. At larger X, on the average they fit the WD (1976) results, including undershooting of the $C_y = 1$ asymptote. This undershoot is due to lofting of most material into the upper half of the mixing layer at intermediate values of X. This phenomenon is seen clearly in 6 of the 8 surface releases in the plots of oil fog $\int Xdy$ versus z shown by Kaimal et al. (1986). Periods 2-83 and 3-83 do not show this behavior, while periods 4-82, 5-82, and 1-83 show lofting at a smaller X than found by WD. Period 1-83 plunges to a particularly low value of C_y at the surface, 0.2, but it is a small $\bar{u}/z_i$ case.

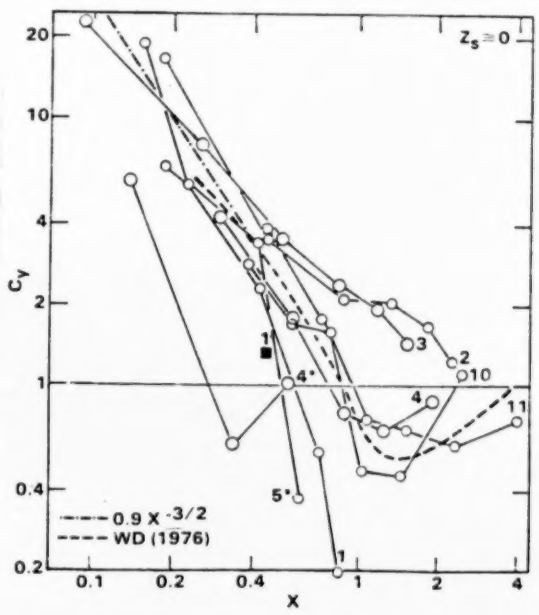

Fig. 4. Near surface C_y vs. X for surface releases compared to WD (1976) and Nieuwstadt's (1980) analytical fit to Prairie Grass field data.

We can conclude that the CONDORS field measurements are consistent with the WD and Lamb laboratory and numerical modeling results, especially for σ_z growth and low-level release σ_y growth. In most experimental periods, surface values of $\int Xdy$ versus x agree with WD's results far better than with conventional Gaussian plume predictions, but there also are much larger deviations from its norm than for σ_y or σ_z.

References

Briggs, G. A., 1985: Analytical parameterizations of diffusion: the convective boundary layer. J. Climate and Appl. Meteor. 24, 1167-1186.

Deardorff, J. W., 1970: Convective velocity and temperature scales for the unstable boundary layer or Rayleigh convection. J. Atmos. Sci., 27, 1211-1213.

Eberhard, W. L., W. R. Moninger, T. Uttal, S. W. Troxel, J. E. Gaynor, and G. A. Briggs, 1985: Field measurements in three dimensions of plume dispersion in the highly convective boundary layer. Preprints, 7th Symposium on Turbulence and Diffusion, Boulder, Amer. Meteor. Soc., 115-118.

Kaimal, J. C., W. L. Eberhard, W. R. Moninger, J. E. Gaynor, S. W. Troxel, T. Uttal, G. A. Briggs, and G. E. Start, 1986: Project CONDORS convective diffusion observed by remote sensors. NOAA/ERL/ Boulder Atmospheric Observatory, Report No. 7 (available from NOAA/ERL, Boulder, CO 80303), 305 pp.

Lamb, R. G., 1978: A numerical simulation of dispersion from an elevated point source in the convective boundary layer. Atmos. Environ., 12, 1297-1304.

Lamb, R. G., 1979: The effect of release height on material dispersion in the convective planetary boundary layer. Preprints 4th Symp. on Turbulence, Diffusion, and Air Pollution, Reno, Amer. Meteor. Soc.

Moninger, W. R., W. L. Eberhard, G. A. Briggs, R. A. Kropfli and J. C. Kaimal, 1983: Simultaneous radar and lidar observations of plumes from continuous point sources. Preprints, 21st Radar Meteorology Conference, Edmonton, Amer. Meteor. Soc., 246-250.

Nieuwstadt, F. T. M., 1980: Application of mixed-layer similarity to the observed dispersion from a ground-level source. J. Appl. Meteor., 19, 157-162.

Willis, G. E. and J. W. Deardorff, 1976: A laboratory model of diffusion into the convective planetary boundary layer. Quart. J. Roy. Meteor. Soc., 102, 427-445.

Willis, G. E., and J. W. Deardorff, 1978: A laboratory study of dispersion from an elevated source in a convective mixed layer. Atmos. Environ., 12, 1305-1313.

Willis, G. E., and J. W. Deardorff, 1981: A laboratory study of dispersion from a source in the middle of the convectively mixed layer. Atmos. Environ., 15, 109-117.

DISCLAIMER - This is an extended abstract of a presentation and does not necessarily reflect EPA policy.